Performance Evaluation of Carrier Aggregation as a Diversity Technique in mmWave bands

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***Abstract*—Millimeter wave (mmWave) frequencies have been selected to provide the high data rates and capacity targeted by the next generation (5G) of mobile communication networks. Compared to the sub 6-GHz bands that have been historically exploited by popular communication systems, mmWave bands suffer from adverse radio propagation degradations such as higher path loss and blockage, however they provide significantly larger bandwidths and lower levels of usage than sub 6-GHz bands. Mobile operators can employ Carrier Aggregation (CA) techniques to combine the newly acquired spectrum in mmWave bands with their already allocated spectrum in sub 6-GHz bands. The use of CA as a technique to combine chunks of spectrum in a transparent manner for higher layers of the protocol stack has been widely researched. In this paper, a different focus is considered by exploring the use of CA as a diversity technique in order to further improve the network capacity under various radio propagation scenarios. The obtained results indicate that CA can effectively be exploited as a diversity technique to optimize the overall system performance and increase the network capacity, with the optimum number of component carriers depending on the radio propagation distance.**

***Index Terms*—Carrier aggregation, mmWave, 5G, NS-3**

I. Introduction

As wireless communication is becoming more of a commodity just like electricity and water, it has given rise to large array of emerging high data rate hungry devices and services [1]. Fifth generation (5G) mobile communication network is evolving and will be characterised by an increase in the number of wireless devices and service types, the availability of different radio access technologies, and the ability to transmit at a high data rate which is expected to meet the data requirement of various high speed multimedia applications [2]- [4]. In order to meet the requirements of various high-speed multimedia applications, wireless communication systems in the next generation are expected to reach the data rate characteristics of 1Gbps. Boosting the transmission rate in these systems is achieved by using larger bandwidth but due to the practical constrains, large segments of continuous spectrum may not be available for most wireless network operators which makes the effective use of plurality of non-continuous frequency spectrum and alternative option [2], [3]. The international research community has carried out research on spectrum expansion technologies to improve a single user's peak data rate with techniques such as Carrier Aggregation (CA). This is the aggregation of both contiguous and non-contiguous spectrum in the licensed and unlicensed bands, which will play an important role in the future of the 5G wireless network with an air interface based on millimeter wave (mmWave) and narrow band cellular IOT coexisting with the LTE network in a carrier aggregation mode [2], [4]. Millimeter wave which is regarded as a promising technology has been stated to address the shortage of spectrum (microwave) in wireless network and has become the saviour of 4G/5G mobile operators as it will be suitable for its coexistence with LTE network [1], [5].

Possible carrier aggregation and millimeter wave band scenarios have been extensively researched, [3], [4] using the channel state information and low computational complexity to improve carrier aggregation technique, mitigate some of the challenges and reduce energy consumption in 5G scenarios. Millimeter wave capabilities extend to support wireless backhaul networks by exploiting the conventional frequency and mmWave bands via carrier aggregation [6]. Statistical channel models researched in both academic and industry obtains a model that capture the physical layer parameters [7], [8], understanding the behaviours and models of this wireless channels (mmWave radio) will proffer real life scenario solutions of carrier aggregation in the 5G radio access network. This work investigate the performance of carrier aggregation over mmWave bands by means of system level simulations. Discrete-event network simulators are fundamental in the development and analysis of complex networks, having an end-to-end cellular system with mmWave carrier aggregation integrated in the ns-3 simulator with models of real life scenarios. The performance of mobile communication networks over two component carriers was simulated in contiguous and non-contiguous allocation in [9], this work extends the simulation to a broader range of propagation scenarios as defined by 3GPP and increases the number of component carriers, investigating the impact of various levels of carrier aggregation in different propagation scenarios and determining the optimum configuration as a function of the propagation and communication context.

The main purpose of CA is to allow operators combine multiple chunks of (possibly non-contiguous) spectrum in a transparent manner for higher layers of the protocol stack so that it can be seen as a single block of spectrum by higher layers. CA techniques from this perspective have been

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widely investigated. However, it is worth noting that CA may also be exploited as a diversity technique. Notice that each Component Carrier (CC) that is aggregated through CA runs an individual instance of the scheduler and therefore the employed transmission parameters such as the modulation and coding schemes are adapted individually to each CC. This suggests the possibility to exploit CA as a diversity technique, even in the case of contiguous blocks of spectrum where the use of CA would not really be necessary in order to exploit that spectrum. In this paper, a different focus is considered by exploring the use of CA as a diversity technique in order to further improve the network capacity under various radio propagation scenarios. The obtained results indicate that CA can effectively be exploited as a diversity technique to optimize the overall system performance and increase the network capacity, with the optimum number of CCs depending on the radio propagation distance.

The remainder of the paper is structured as follows. First, the simulation methodology and carrier aggregation model considered in this work are explained in II. Then III presents and analyses the obtained simulation results for the different scenarios, drawing the most relevant conclusions and findings derived from this work. Finally, IV summarises the main conclusions derived from this study and concludes the paper.

II. Methodology

This work investigates the performance of carrier aggregation over mmWave bands by means of system level simulations. It is important to have an end-to-end simulation system that can exploit the capabilities of mmWave links across all communication protocol stack. In [10] a full stack module ns3-mmWave module is developed, integrated into the widely used open source ns-3 simulator, which includes a good number of detailed statistical channel models and ability to incorporate measurements or ray tracing data. This module has a modular and highly customizable physical and medium access control layers and interfaced with the core ns-3 Long term Evolution (LTE) module network for the full stack end-to-end connectivity. The implementation of carrier aggregation for the ns-3 mmWave module with the 3GPP New Radio (NR) at mmWave frequencies is simulated as a multi connectivity technique for the same RAT which is combined at the User Equipment (UE) side. Different data streams can be transmitted in each link which are called component carriers (CC) using different frequencies. The component carrier can be adapted to the channel independently i.e. using different scheduling instances, Modulation and Coding Schemes (MCSs) and retransmission processes when needed, all in the same base station design combining carriers with different propagation properties in both licensed and unlicensed bands up to 16CC supported in the 3GPP NR standard [9]. Differnt distance was simulated in Line of Sight (LOS) and Non-Line of Sight (NLOS) with Urban Macro (UMa), Urban Micro (UMi-StreetCanyon), Rural Macro (RMa), InH-OfficeMixed, InH-OfficeOpen and Indoor Shopping Mall scenarios as detailed in the 3GPP channel model calibration where the UE is at a fixed distance from the Base Station (BS) [11]. This adjustable distance is based on the validity of the propagation models for each of the scenarios with bandwidth of 1 GHz assigned to a single carrier and when CA is enabled, each of the two component carriers will be assigned 500 MHz each. Multiple component carrier simulation is implemented in the simulator to evaluate the impact of the number of component carriers on the UE avarage throughput. The suitability of carrier aggregation as a diversity technique is evaluated by considering a contiguous block of spectrum with a total bandwidth of 1 GHz and subdividing into a number of contiguous chunks, each of which is managed as a seperate component carrier that is aggregated to the other component carriers in the same 1 GHz spectrum block.

III. Simulation Results and Discussion

This section presents simulation results assessing the performance of CA in mmWave bands not only as a way to allow mobile operators to aggregate several spectrum bands in order to gain additional capacity but also as a diversity technique to improve the performance of the already allocated spectrum. Simulations are carried out with the ns-3 simulatior using the configuration shown in Table 1.

TABLE I
Table of main simulation parameters.

Number of eNB	1	
Number of UE	1	
BS-UE dictance	10m-5500m	
Propagation scenarios	UMa, RMa, UMi, InH-Office	
Propagation conditions	LOS/NLOS	
Total amount of spectrum	1 GHz	
Number of CC's	1-5	
CC bandwidth	1/no. of CC's	
Simulation time	5 min.	
Contiguous Freq.(GHz)	f0 = 40	(f0 = 39.75, f1 = 40.25)
Non-contiguous Freq.(GHz)	f0 = 73	(f0 = 32.5, f1 = 73)

The impact of carrier aggregation is firstly evaluated considering a total amount of spectrum of 1 GHz bandwidth, which the operator can exploit as a single block with a single CC or two blocks with a spectrum split ratio of 0.5 between the primary and secondary CCs, with central frequencies of 39.75 GHz and 40.25 GHz for contiguous carrier aggregation and 32.5 GHz and 73 GHz for non-contiguous carrier aggregation. The user is placed at a fixed distance from the base station under both Line of Sight (LOS) and Non-Line of Sight (NLOS) conditions. The possibility of blockage is considered as well, thus expanding the range of propagation scenarios. the performance is assessed in terms of the throughput experienced at the Radio Link Control (RLC) layer of the protocol stack.

Fig. 1 shows the system performance under UMa propagation scenario with LOS. As it can be expected, CA helps increase the overall system throughput. Both configurations with two CCs provide a significantly greater throughput than both configurations with only one CC. One can also notice that the experienced throughput is highly dependent on the centre frequency considered, with transmissions at lower frequencies

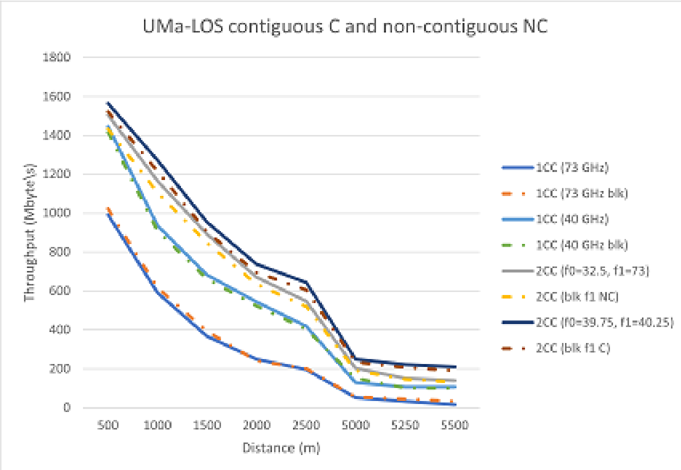

Fig. 1. Contiguous and non-contiguous UMa-LOS received throughput by the distance.

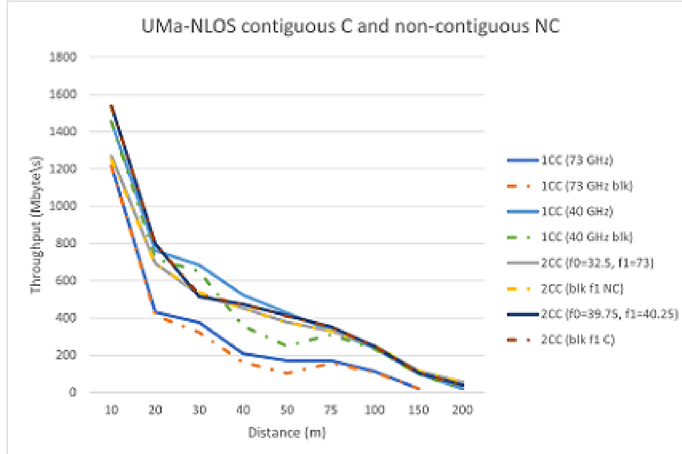

Fig. 2. Contiguous and non-contiguous UMa-NLOS received throughput by the distance.

experiencing higher throughputs because of the reduced path loss. However, it is also interesting to note that the use of CA can help reduce the impact of path loss throughput degradation, since this effects to a larger extent when only one CC is considered. Notice that, when only one CC is employed, the difference between the throughput at 40 GHz and 73 GHz can be up to around 400 Mbit/s (more than 20 % performance degradation). However, when two CCs are considered, the throughput difference between the configurations using CCs at 40.25 GHz and 73 GHz give a more similar throughput. The throughput is slightly higher when both CCs are contiguous at lower frequencies (39.75 GHz and 40.25 GHz), but if one of the CCs is moved to a higher carrier frequency (73 GHz) then throughput degradation is quite light and significantly lower than that observed if the same change of carrier frequency is applied when only one CC is used. This can be explained by the propagation diversity offered by CA. On the other hand, the presence of blockage appears to have a slightly more severe impact on the throughput when two CCs are used instead of only one, however such degradation is not very significant; notice that the CA case considers blockage in the lower-frequency CC where its effect is more severe (even with full blockage in both CCs the throughput would still be similar). In general, the use of CA with two CCs in the presence of blockage still provides significantly higher throughput than the use of one single CC even if it is not experiencing any blockage. Therefore, it can be seen that CA not only provides a higher overall throughput compared to the use of a single CC but also makes the obtained throughput performance less sensitive to the particular radio propagation frequencies of the CCs as a result of the propagation diversity arising from the combination of several CCs.

Fig. 2 shows the counterpart to Fig. 1, also considering an UMa propagation scenario, but in this case under NLOS conditions. It can be observed that, in this other case, the performance difference between the use of CA with two CCs and the use of a single CC with no CA is not so significant. In fact, while there is still a clear difference between using a single CC at 40 and 73 GHz, there is no practical difference between the two configurations with two CCs (contiguous and non-contiguous spectrum). In fact, the use of two CCs in both configurations leads virtually to a very similar performance, which is indeed very similar to the performance attained with the use of one single CC at 40 GHz and, at some distances, even slightly lower. This slightly lower performance of CA can be explained based on the fact that under NLOS conditions the practical propagation distances are reduced significantly (as it can be noticed by comparing the abscissas axes of Fig. 1 and 2) and at such shorter distances the path loss does play such an important role, therefore the potential gain that CA could provide as a diversity technique is not large enough to compensate for the overhead associated with the use of CA (mainly, the use of guard bands between CCs that reduce the overall spectrum efficiency and the extra signalling overhead involved in the use of CA). In this case, under NLOS conditions, it seems that the use of the whole spectrum available as a single chunk with one single CC, where possible, should provide a better throughput performance. It is worth noting that the observations made above for the UMa scenario are in general applicable to other propagation scenarios as well. The same trends were observed for other macro scenarios such as the RMa propagation model (results not shown due to the lack of space), micro scenarios (see, as an example, the results obtained for UMi-LOS in Fig. 3) and even indoor environments (see, as an example, the results obtained for InH-Office in Fig. 4). It can be noticed that the full potential of CA as a diversity technique can be exploited in macro scenarios and under LOS conditions, with the experienced blockage being a secondary aspect.

To further explore the performance of CA as a diversity technique, we now consider a single contiguous block of spectrum with a bandwidth of 1 GHz where the operator can opt to exploit it as a single block of spectrum with one single CC or, by using the principles of CA, as multiple blocks of

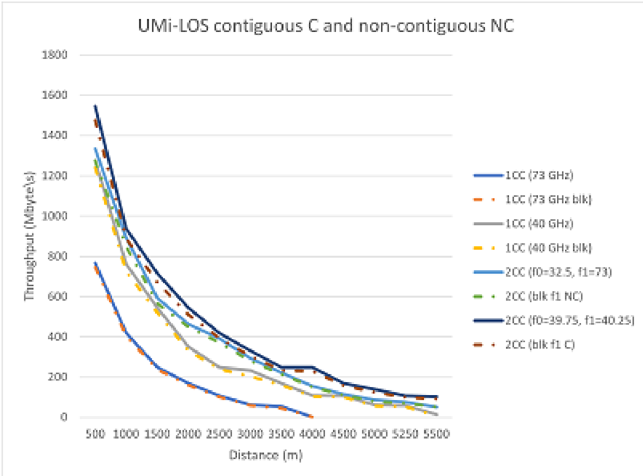

Fig. 3. Contiguous and non-contiguous UMi-LOS received throughput by the distance.

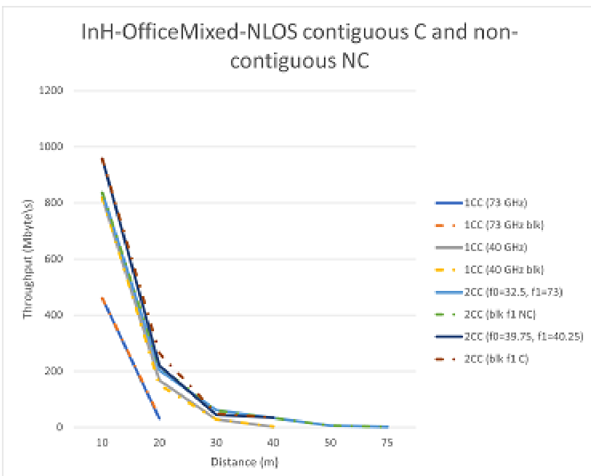

Fig. 4. Contiguous and non-contiguous InH-OfficeMixed-NLOS received throughput by the distance.

spectrum each with its own CC, where the available spectrum is divided into a number of contiguous CCs with carrier frequencies as shown in Table 2. Notice that in this scenario there would be no need to use CA techniques since the whole block of spectrum is contiguous and the operator could use a single CC. However, we investigate here the possibility of splitting the block into a number of contiguous CCs that are exploited using CA. The motivation to consider this approach is to explore the potential benefits that CA could bring as a diversity technique.

Fig. 5 shows the throughput performance observed under an UMa-NLOS propagation scenario when the number of CC is increased from one to five. The UMa-NLOS propagation scenario is here selected because it provides more accurate results than the other available scenarios, however similar conclusions can be drawn for other scenarios as well. The results in Fig. 5 indicate that the optimum number of CCs increases with the distance, which is shown more clearly

TABLE II
TABLE OF COMPONENT CARRIER FREQUENCY AND BANDWIDTH ALLOCATION.

No of CC	BW per CC (MHz)	Carrier Frequency (GHz)				
1	1000	40				
2	500	39.75	40.25			
3	333.3	39.67	40	40.33		
4	250	39.63	39.88	40.13	40.38	
5	200	39.6	39.8	40	40.2	40.4

in Table 3. In general, increasing the number of CCs increases the ability of the system to exploit any available radio propagation diversity since each CC is handled individually with its own scheduler instance. However, a higher number of CCs also incurs in a higher overhead resulting from the higher signalling required to handle each CC along with the presence of some guard bands between CCs (which contributes to decrease the overall spectrum efficiency). For CA to be beneficial as a diversity technique, the gain obtained from channel diversity needs to outperform the penalty associated with a higher number of CCs. The trade-off between both aspects determines the optimum number of CCs for each propagation distance as observed in Fig. 5 and Table 3. At shorter distances, the channel diversity is not significant (e.g., the path loss experienced at different CCs over short distances is very similar) and therefore a lower number of CCs provides the highest throughput, while at longer distances the radio propagation gain diversity increases and therefore the optimum number of CCs increases. These results indicate that CA can therefore be exploited as a diversity technique to optimize the overall system performance, with the optimum number of CCs depending on the radio propagation distance.

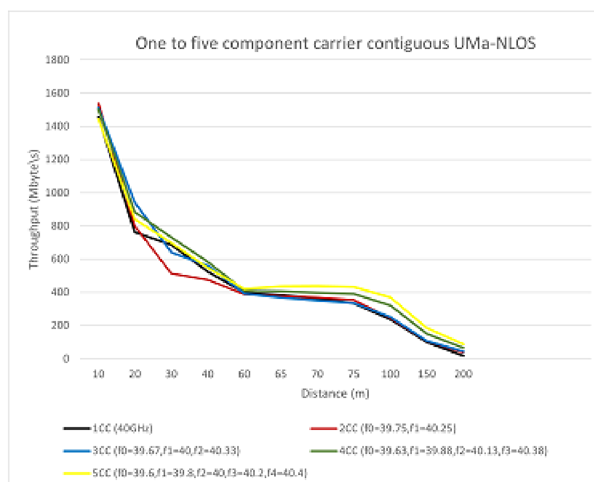

Fig. 5. One to five component carrier contiguous UMa-NLOS simulation.

IV. Conclusion

Carrier Aggregation (CA) was originally proposed as a technique to allow mobile operators combine spectrum from

TABLE III
UMA-NLOS SIMULATION RESULT TABLE FOR 1CC TO 5CC.

Distance(m)	1CC	2CC	3CC	4CC	5CC
10	1455.5	1537.2	1510.4	1499.7	1445
20	762.1	797.6	941	884.4	839.4
30	684.9	513.8	639.3	730.5	698
40	524.2	474.5	560.9	583.2	547.9
60	397.5	388.7	392.2	410	421
65	383.7	377.8	367.9	405.5	435.6
70	364.8	368.3	351	398.3	437.7
75	332.7	352.5	334.5	390.5	432.5
100	236.7	245.5	250.9	320.6	369.1
150	99.2	104.4	106.5	150.3	184.9
200	18.3	38	44.2	64.7	87.9

different bands into a single virtual chunk of spectrum that could be seen by the higher layers of the protocol stack as a single block of spectrum. Each aggregated Component Carrier (CC) runs its own scheduler instance and therefore adapts its own modulation and coding scheme and retransmission process individually according to the CC's propagation conditions. This allows CA to be potentially seen as a diversity technique. In this paper, a different focus has been considered where the suitability of CA as a diversity technique has been explored. The performance of CA under various propagation scenarios has been evaluated and analysed. The obtained results indicate that CA can effectively be exploited as a diversity technique to optimize the overall system performance and increase the network capacity, with the optimum number of component carriers depending on the radio propagation distance.

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